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Cost estimates in cost-effectiveness analysis of water quality monitoring systems

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Abstract: Traditional cost-effectiveness analysis requires obtaining estimates of the cost and effectiveness of a monitoring program or design and weighing them against each other. With obvious technical soundness of the approach, its complete utilization, however, is still very limited. The limitations should be attributed firstly to the necessity to express both the cost of a monitoring program and its effectiveness in quantitative terms using at least the same measurement units, if the monetary estimates are not available. Although the cost estimation is considered as a simple technical exercise, it is worth noting that comprehensive and systematic guidelines for developing cost estimates of an environmental monitoring program are not available. In most of the cases, when evaluating the cost of a monitoring program, the authors take into account only some of the components and even for those components estimates are very approximate or are not available at all. When monetary estimates of the effectiveness and the cost of a monitoring program are unknown, the direct cost-effectiveness analysis can be replaced by an operation research model, solutions to which generate efficient monitoring designs. One of the two possible articulations of the optimization problem is to minimize the cost of a program or design, so that the effectiveness of the program meets established requirements. In this case, mathematical articulation of the cost serves as the goal function. The effect of a particular expression for this function on the designs developed as solutions of the constraint optimization problem is investigated in the study.

The analysis of the scientific and technical literature on cost-effectiveness analysis of environmental and ecological monitoring programs revealed different approaches to cost estimates with the emphasis on the necessity to distinguish between budgetary costs, showing how the allocated money is spent and economic costs which broaden the consideration and add the opportunity cost, i.e. the missing benefits of other activities due to allocating the money to monitoring an environmental resource. The comprehensive cost assessment should include both components, however, the approaches to complete cost estimates are yet to be developed. Since the cost function is intended for application in the operation research model for developing efficient temporal monitoring designs, only budgetary cost is considered under an assumption that variable cost is associated solely with water sample collection and processing. The rest of the cost components are independent of the number of taken samples and constitute the fixed cost. In all suggested approaches, the cost of a program is defined as a non-negative, non-decreasing function of the number of samples collected or observations made. Seven mathematical expressions were developed with the same properties and their parameters were identified based on rough estimates of the costs of operations of a water quality monitoring system. The effect of the cost articulation on the developed designs was investigated through a series of computational experiments, where the designs were developed as solutions of the optimization problem with different mathematical expressions for the goal function.

The results of computations showed that the solutions of the optimization problem are invariant of the expressions used for the cost function. The designs for monitoring water constituents remained unchanged when the developed expressions with different mathematical functions were substituted into the cost function. The study showed that, the optimal number of observations is independent of the cost of a monitoring design. It is determined by the level of effectiveness which must be attained by the design. The results validate the replacement of the cost-effectiveness analysis in its classical form by an operation research model which minimizes the total number of observations with the limit set for required effectiveness. Solutions of this model will generate designs with minimal cost.

Keywords: *Monitoring designs, cost-effectiveness analysis, constraint optimization, water quality*

1. INTRODUCTION

There is no need to convince practitioners in the usefulness of cost-effectiveness analysis for developing effective environmental monitoring programs. Frameworks based on such analysis have been proposed for years (e.g., Groot and Schilperoort, 1983) with the main suggestion – to obtain cost and effectiveness estimates and to weigh them against each other. With obvious technical soundness of the approach, its complete utilization is still very limited. The limitations should be attributed primarily to the necessity to express both the cost of a monitoring program and its effectiveness in the same measurement units, preferably in monetary terms. Traditionally, the effectiveness caused major difficulties and disagreements on how to define and quantify it with respect to the process of environmental data collection, while the cost estimation was considered as a simple technical exercise. It is worth noting that comprehensive and systematic guidelines for developing cost estimates of an environmental monitoring program are not available. In most of the cases, when evaluating the cost of a monitoring program, the authors take into account only some of the components and even for those component estimates are very approximate or not available.

When monetary estimates of the effectiveness and the cost of a monitoring program are unknown, the direct cost-effectiveness analysis can be replaced by an operation research model, solutions to which generate efficient monitoring designs. This replacement has been implemented for developing efficient temporal designs for a water quality monitoring system (Erechtchoukova and Khaiter, 2009; Erechtchoukova et al., 2009). The approach is based on two assumptions: (1) both the cost and the effectiveness can be expressed as functions of the number of observations, and (2) the cost of a design is a linear function of the total number of observations. The operation research model for optimization of monitoring activities can be formulated in dual form (e.g., Erechtchoukova and Khaiter, 2010). One of these articulations with the assumption (2) was used to avoid explicit evaluation of the cost of a monitoring program and replace it by the total number of required observations.

In this study, the role of explicit formulation of the cost function in the operation research model for optimization of monitoring designs is investigated. Temporal monitoring designs for a routing water quality monitoring system with the fixed network of observation sites are considered with respect to various articulations of the cost. In the outset, a brief overview of the cost estimates and their underlying assumptions is given in the following section of the paper. The analysis of these assumptions provides insights into mathematical properties of the function evaluating the cost of a monitoring program in general and a monitoring design in particular. Several mathematical formulae are created and used for developing monitoring designs. Derived properties of the cost function are used for analytical consideration and to justify reformulation of the operation research model such that the explicit cost estimates are not required. The conclusions are supported by a set of computational experiments which were conducted using data collected by the Toronto and Region Conservation Authority on a small river with a highly urbanized watershed.

2. MONITORING COST

As a rule, environmental monitoring systems including water quality monitoring systems are funded by federal and/or local governments which implies, that the money spent on monitoring activities is always under the public scrutiny. The cost of a monitoring program is one of the critical characteristics which are used to justify the request for fund allocation or to provide rational for a certain management decision. Approaches to cost estimation reported in the literature use different sets of assumptions and consider different types of cost. Thus, Caughlan and Oakley (2001) distinguished between budgetary costs showing how the allocated money is spent and economic costs which broaden the consideration and add the opportunity cost, i.e. the missing benefits of other activities due to allocating the money to monitoring an environmental resource.

2.1. Economic costs of a monitoring program

There is a unanimous agreement on the necessity to consider an economic cost of monitoring activities reflecting the complete set of cost components when the monetary appraisal is implemented for a monitoring program (Caughlan and Oakley, 2001). The economic cost provides more comprehensive evaluation of the program and can demonstrate a necessity for long-term environmental observations. The economic cost must include an opportunity cost in addition to budgeted estimates. The opportunity cost reflects potential services of a resource missing due to the allocation of funds to the monitoring program rather than other related activities. As a rule, an environmental resource has both commercial and non-commercial potential which should also be considered when the economic cost of a monitoring program is derived (Rahman and

Devadoss, 2009). To evaluate an opportunity cost, Loomis and Walsh (1997) suggested identification of direct and indirect consequences and benefits of recreational usage of a natural source. A similar approach should be applied while evaluating a monitoring program. The consequences of the program may even include adverse effects of missing an important event or change in the observed environment. For example, Field et al. (2004) developed the cost functions incorporating an estimate of probability that a deleterious change has occurred, the probability that monitoring data will correctly support a conclusion whether the change has occurred, and the monetary cost of actions invoked by the conclusion. A complete list of such benefits is hard to achieve. Moreover, even if the extensive list of consequences is generated, monetary estimates of these items are not readily available. Some of these benefits can be assigned a dollar value based on their market value or subsidized costs. Other benefits have non-market values. To obtain their estimates existing approaches require further elaboration. Thus, for industrial pollution, the economic cost of a monitoring program may include ecological fines and legal penalties for violations of existing environmental standards (Harford, 2000). However, these cost components do not cover all opportunities.

2.2. Budgetary estimates of a monitoring program

In general, budgetary cost should cover two distinct periods of a monitoring program lifecycle: the development cost and the cost of regular operations. The latter can be further itemized into the following categories of activities: (1) scientific supervision, (2) data collection, (3) data management, (4) quality assurance, (5) data analysis and reporting, and (7) administration, with the second category consuming up to 70% of the allocated budget (Caughlan and Oakley, 2001). It is expected that improvements of these activities can notably reduce the cost of an entire monitoring program. When this type of cost is evaluated, along with dollar values, the time required to complete each operation can also be used as a measure of the cost (e.g., Wildish et al., 2001). According to Mooney et al. (2004), the total budgetary cost of data collection is a sum of fixed and variable costs. The fixed cost comprises planning and organization costs, transportation of the crew to sampling sites, and labour cost during transportation etc. It is independent of the number of collected samples. The cost of labour, equipment and other resources used for sample collection and shipping to analytical laboratories depends on the number of samples taken and is variable. The more samples are collected, the higher the cost.

2.3. Cost of temporal water quality monitoring designs

The variety of approaches to cost estimates and their complexity dictates the necessity for clear articulation of assumptions in order to develop a cost function. The cost function is intended for application in the operation research model for developing efficient monitoring designs. The study focuses on developing temporal monitoring designs for individual observation sites of a stationary water quality monitoring system. The designs determine frequencies of water sample collection at the same location of a waterbody. Only the budgetary cost is considered further with an assumption that variable cost is associated solely with water sample collection and processing. The rest of the cost components are independent of the number of taken samples and constitute the fixed cost *FixedC*. The variable cost reflects monetary estimates of operations with samples and can be approximated using the following function:

$$CostV\,(n) = C * n + g(n)\,, \tag{1}$$

where n is the total number of observations in the design, C is the constant cost of collection of a sample, g is the non-linear function reflecting the costs of sample transportation and processing. Function g is a monotonically increasing function of the number of collected and processed water samples, however, it increases slower than the linear component of the cost. Under the above assumptions, the total cost of a monitoring design is expressed as:

$$D\cos t(n) = FixedC\ + C * n + g(n)\,, \tag{2}$$

Formula (2) represents a non-negative non-decreasing function of the total number of observations suggested by a monitoring design. To evaluate the actual cost of a monitoring design, particular mathematical expressions for $g(n)$ must be specified.

3. THE CONSTRAINT OPTIMIZATION PROBLEM

Cost-effectiveness analysis of monitoring designs compares the design cost against its effectiveness and suggests at least satisficing schemes for water sample collection. The designs are selected so that they maximize the effectiveness of the design under limited budget or minimize the cost of the design within an acceptable level of effectiveness. In both cases it is necessary to provide quantitative estimates of the cost and the effectiveness of a monitoring design as functions of the number of samples. When the cost of a program is used as a constraint, the exact allocated budget should be known. Alternatively, the cost of a program or design can be minimized so that the effectiveness of the program meets established requirements. A few possible articulations of effectiveness as a function of the number of observations have been considered before for an individual water quality parameter (e.g., Erechtchoukova and Khaiter, 2010). An approach to the development of the monitoring designs common for water quality parameters derived from the same water sample is described in (Erechtchoukova and Khaiter, 2012; Erechtchoukova et al., 2013). The approach uses dependencies between water quality parameters described by regression functions. In this study, the effectiveness is expressed via the uncertainty of estimates derived from the data collected according to a monitoring design, and the cost function (2) is used as the goal function of the operation research model, solutions to which generate efficient temporal monitoring designs:

$$\min D\cos t(n) \text{ subject to}$$

$$\left|\frac{D(I_k(C_k,n))}{I_k(C_k,n)}\right| \cdot 100\% \le V_k,\ k = 1,\ldots,K, \tag{3}$$

$$C_k = f_k(C_{CMV}), \tag{4}$$

$$D(I_k(C_k,n)) = D(I_k(f_k(C_{CMV}),n)), \tag{5}$$

where $I_k(C_k,n)$ is the estimator of the k-th water constituent on a set of n observations, $D^2(I_k(C_k,n))$ is the variance of the estimator $I_k(C_k,n))$, V_k is the acceptable level of uncertainty in this estimate, and K is the total number of water constituents of interest, C_{CMV} is the concentration of the water constituent with the least coefficient of variation, f_k is a regression function identified based on the least squares fitting.

4. CASE STUDY

4.1. Monitoring problem

The operation research model (3) – (5) with *Dcost* function equal to *n* was earlier applied to develop efficient monitoring designs at the observation sites of a few rivers with different hydrological characteristics (e.g., Erechtchoukova et al., 2013). One of the rivers, the Humber River, was chosen for the present study. The Humber River (Ontario, Canada) is classified as a small river with the annual water discharge of 0.20–0.32 km^3/year. The main branch of the Humber River flows more than 120 km through a 908 km^2 watershed covering the Niagara Escarpment, the rolling hills and kettle lakes of the Oak Ridges Moraine, the high-quality agricultural lands of the South Slope and Peel Plain, and the ancient Lake Iroquois shoreline. The data were collected at the Old Mill Road station located at the lower part of the main section of the Humber River. This site belongs to the Toronto and Region Conservation Authority monitoring network. The annual hydrograph of the river at the observation site for 1995 is presented in Figure 1.

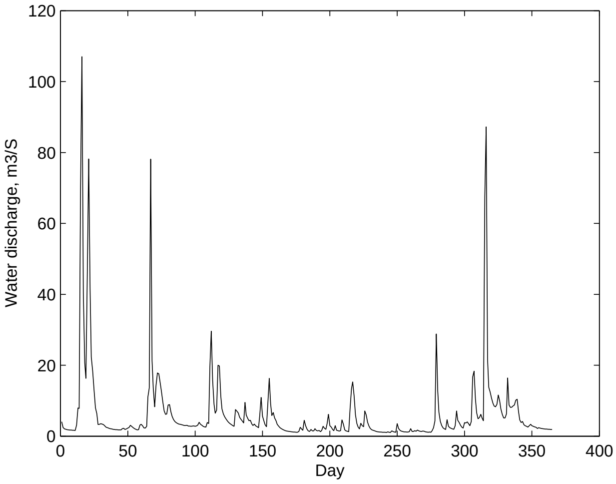

Figure 1. The annual hydrograph of the Humber River at the observation site (Erechtchoukova et al., 2013)

The annual monitoring designs were developed for the following water quality parameters: total calcium (Ca), organic carbon (C), total magnesium (Mg), and total chloride (Cl) ions using polynomial regression functions. The designs common for all four selected water constituents were developed to evaluate their

Table 1. The total number of required observations vs. uncertainty

Uncertainty, %			
5	10	15	20
206	89	46	27

average concentrations with different levels of uncertainty (Table 1).

4.2. Cost functions used in the study

To investigate the influence of the cost function (3) on proposed monitoring designs, seven mathematical expressions were considered. The mathematical expressions for the cost functions are presented in Table 2. In the simplest case, the cost function was equal to the total number of observations per year. In this case, no parameter was identified. For other investigated expressions, some rough estimates presented in (US EPA, 1976) were used in the identification process. Thus, the fixed cost per observation site was assumed \$360.00 per year. The cost of a single grab sample was estimated as \$40.00. The cost of sample transportation and the subsequent laboratory analysis was averaged at \$15.00 per water quality parameter. In addition to that, the parameterization of the last version of function *g* has been done under the assumption that when a large number of samples are processed the cost of processing a single sample decreases by up to three times.

Table 2. Mathematical articulation of the cost function

No	Expression
1	n
2	360+ 40*n + 15*sqrt(n)
3	360 + 40*x + 100*sqrt(n)
4	2.5*n + 6.3*sqrt(n)
5	360 + 40*x + 100*log(x)
6	2.5*x + 6.3*log(x)
7	360 + 40*n + 15*n/(n+2.02)

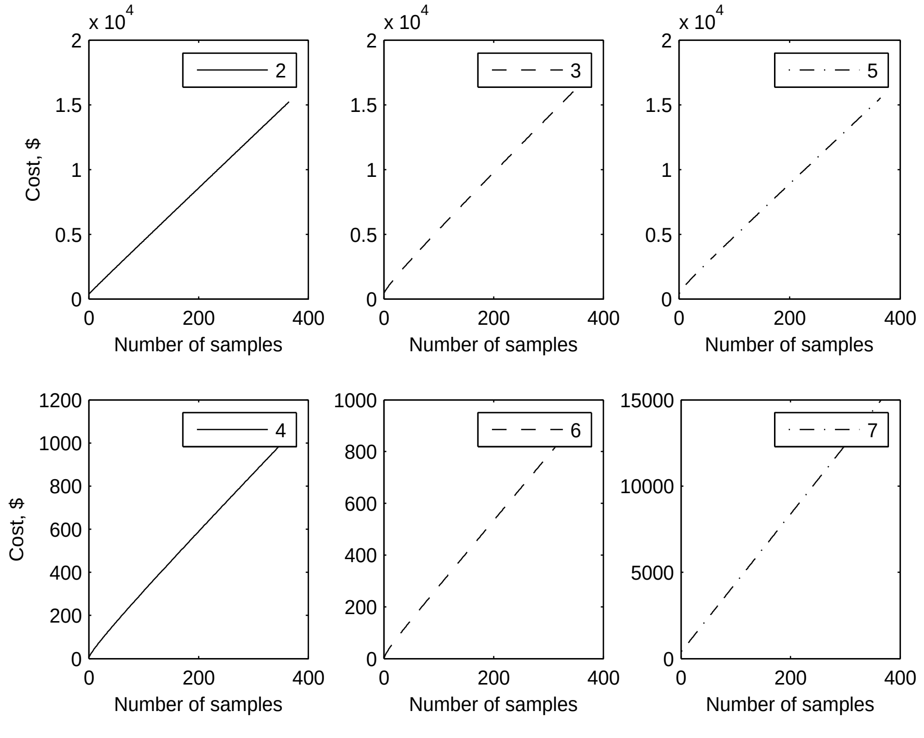

Figure 2. Investigated cost functions

The model (3) – (5) with the cost functions presented in Table 2 was used to developed temporal monitoring designs for individual water quality parameters and designs common for all four investigated water constituents. All developed designs support evaluation of the annual average concentrations of these parameters with different levels of uncertainty. For all expressions in Table 2, the suggested common monitoring designs remain the same as presented in Table 1. The design for monitoring individual water constituents also stayed unchanged when expressions from Table 2 were substituted into function *Dcost*(*n*).

5. DISCUSSION AND CONCLUSIONS

The results of computations showed that the solutions of the operation research model (3) with regression functions (4)-(5) are invariant of the expression used for the cost function. Parameters of the cost functions were identified using historical values which must be adjusted according to the present values of costs for standard economic analysis. These adjustments are not required when data are used in model (3)-(5) due to the demonstrated invariant property of its solutions.

All expressions in Table 2 exhibit common general properties of the budgetary cost estimates, namely, they are non-negative non-decreasing functions of the total number of observations n. The properties were derived based on common sense and are supported by the analysis of economic literature and technical reports on cost estimates of environmental resources and monitoring systems. The domain of n is a bounded set of positive integer values. The minimum of a function with such properties can be achieved only at the lower boundary of the domain of variable n. The constraint functions of model (3)-(5) determine this lower boundary. Therefore, the optimal number of observations is independent of the cost of a monitoring design. It is determined by the level of effectiveness which must be attained by the design.

The lower boundary of the domain of variable n varies for different expressions describing the effectiveness of a monitoring program or its designs. Quantitative evaluation of effectiveness of a monitoring program which was considered as the main obstacle for application of the cost-effectiveness analysis for years remains important for developing sample collection schemes. Some alternative articulations of effectiveness in mathematical terms were described earlier. Investigation of their properties and the constraints imposed by the effectiveness functions are subject to further investigation.

The results validate the replacement of the cost-effectiveness analysis in its classical form by an operation research model which minimizes the total number of observations with the limit set for required effectiveness. Solutions of this model will generate designs with minimal cost.

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